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Design and operation of urban wastewater systems considering reliability, risk and resilience

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A B S T R A C T

Reliability, risk and resilience are strongly related concepts and have been widely utilised in the context of water infrastructure performance analysis. However, there are many ways in which each measure can be formulated (depending on the reliability *of what*, risk *to what from what*, and resilience *of what to what*) and the relationships will differ depending on the formulations used. This research has developed a framework to explore the ways in which reliability, risk and resilience may be formulated, identifying possible components and knowledge required for calculation of each and formalising the conceptual relationships between specified and general resilience. This utilises the Safe & SuRe framework, which shows how threats to a water system can result in consequences for society, the economy and the environment, to enable the formulations to be derived in a logical manner and to ensure consistency in any comparisons. The framework is used to investigate the relationship between levels of reliability, risk and resilience provided by multiple operational control and design strategies for an urban wastewater system case study. The results highlight that, although reliability, risk and resilience values may exhibit correlations, designing for just one is insufficient: reliability, risk and resilience are complementary rather than interchangeable measures and one cannot be used as a substitute for another. Furthermore, it is shown that commonly used formulations address only a small fraction of the possibilities and a more comprehensive assessment of a system's response to threats is necessary to provide a comprehensive understanding of risk and resilience.

1. Introduction

Reliability and risk have been widely used as the primary criterion in water infrastructure design and operation. Conventional design aims to provide a high degree of reliability (Butler et al., 2017) and risk analysis is commonly used to address the response to threats. However, there are limitations to risk assessment: not all risks can be quantified due to the existence of emerging and unobserved threats (Park et al., 2013), unforeseeable threats cannot be included, and highly improbable events which have a high degree of uncertainty are dealt with poorly. Only threats which are known and can be assigned a probability can be analysed, so calculated risk depends on what is and is not known (Kaplan and Garrick, 1981). In recent years, the resilience concept has evolved and is beginning to be incorporated in the design and operation of various water systems, sometimes in combination with risk and reliability (Asefa et al., 2014; Hoque et al., 2012). However, the relative importance of these three terms, their interdependencies and their impact on system performance are currently poorly understood.

Reliability, risk and resilience are strongly related concepts (Scholz et al., 2011) and the relationship between reliability and risk has been well developed in the context of infrastructure performance analysis. There have also been more recent studies into relationships with resilience. The US Homeland Security Studies and Analysis Institute (2010), for example, comprehensively studied risk and resilience relationships (qualitatively and quantitatively), by generating a risk-resilience matrix and adopting of mathematical methods to identify influencing factors in a system. The ETH Zürich Centre for Security Studies (2011) conceptualized the risk and resilience relationship using three different perspectives that

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have been implicitly adopted in several subsequent studies: a) considering resilience 'as a goal of risk management' (Ongkowwijoyo and Doloi, 2018; Serre and Heinzlef, 2018); b) considering it 'as part of risk management' (Hoque et al., 2012; Kammouh et al., 2017; Mitchell and Harris, 2012; Shafieezadeh and Burden, 2014); and c) considering it 'as an alternative/complementary to risk management' (Homeland Security Studies and Analysis Institute, 2010; Joyce et al., 2018; Kammouh et al., 2017; Park et al., 2013). The latter argues that risk and resilience are differentiable concepts but interrelated, complementary, mutually reinforcing and could be coupled to improve adaptive capacity of engineering systems.

Whilst risk and resilience have previously been compared conceptually (e.g. Aven, 2011; Baum, 2015), there are many ways in which each term can be formulated (depending on the reliability *of what*, risk *to what from what*, and resilience *of what to what*) and the relationships will differ depending on the formulations used. It is recognised that resilience, for example, can exist at different scales, time periods and systems, and there may be trade-offs between these which are key to the assessment and management of resilience (Chelleri et al., 2015). However, the multiple different ways in which resilience can be formulated have not previously been formalised. Risk has previously been decomposed using a matrix approach to show the links between multiple 'initiating events', intermediate states and final damage states (Kaplan et al., 1983), but analysis of specific formulations was not carried out. The current lack of understanding of all the ways in which reliability, risk and resilience can be formulated within the same framework poses a barrier to a comprehensive understanding of their relationships and comparison on a like-for-like basis.

Urban wastewater system studies have typically aimed to reduce level of service failures under design conditions (i.e. increase reliability) (e.g. Juznic-Zonta et al., 2012; Oliveira and Von Sperling, 2008), and there has also been research into risk (e.g. Astaraie-Imani et al., 2012) and resilience (e.g. Matthews, 2016; Schoen et al., 2015; Scott et al., 2012) individually. Resilience analysis can provide additional understanding of wastewater system performance, provide greater scope than risk analysis and account for a wider range of threats (particularly those that are low-probability and high-impact). It can also provide greater insight into the failure characteristics, since it is commonly assumed to be dependent on both the magnitude and duration of failures (Butler et al., 2016; Mugume et al., 2015). There is also an increasing interest in building resilience in practice, as evidenced, for example, by the 'resilience duty' imposed in the UK Water Act (HM Government, 2014), and the rapid growth in the publication of papers relating to resilience in a range of fields.

Juan-García et al. (2017) conducted a comprehensive and critical review of the state of the art in resilience assessment in wastewater systems management and defined future research directions that will contribute to the operationalisation of resilience; however, the relationship between risk and resilience and whether, for example, resilience analysis can replace risk assessment, is still unclear. With respect to reliability, risk and resilience, there is a lack of studies on wastewater systems that consider all three metrics as separate criteria for design and operation and explore their relationships both conceptually and quantitatively. Wang and Blackmore (2012) calculated separate values for each; however, these were for a rainwater harvesting system and, whilst they were all used to inform the design process, the relationships between the performance measures was not explored. Other publications focusing on different water systems have also not evaluated all three metric and/or explored their relationships in a quantitative manner. Blackmore and Plant (2008), for example, discussed the differences between risk management and resilience approaches, but did not explore these in a case study and did not undertake a quantitative analysis. Reliability was not discussed. In other studies that have used a case study and provided a quantitative analysis (e.g. Su et al., 2018), resilience has been considered a component of risk assessment – separate risk and resilience values have not been computed and risk and resilience have not been compared.

This paper, therefore, presents an innovative framework to explore the relationships between reliability, risk and resilience levels provided by multiple operational control and design options for a case study integrated urban wastewater system (IUWS: sewer catchment, wastewater treatment plant and receiving river considered as a whole). In this, the multiple ways in which reliability, risk and resilience can be formulated are captured and formalised in a single framework for the first time, and the potential advantages or disadvantages of each formulation are investigated. The framework also reveals the prerequisite knowledge required for calculations under each formulation, clearly illustrating the differences between what can be addressed by reliability risk and resilience assessments. This research builds upon the Safe & SuRe framework (Butler et al., 2016), which shows how threats to a water system can result in consequences for society, the economy and the environment, to enable the formulations to be derived in a logical manner and to ensure consistency in any comparisons.

This paper does not aim to quantify the correlations between reliability, risk and resilience in a general sense (although numerical values specific to the case study are presented and discussed), as the numerical values will vary depending on the system evaluated. However, formalisation of the conceptual formulations of each measure illustrates the overlap in what is addressed by each, as well as the differences.

The conceptual decomposition of reliability, risk and resilience into all their possible formulations provided in this study, enables future analyses to be placed within the wider picture, ensuring that any comparisons are made on a suitable basis and using compatible formulations. The results also highlight the gaps in many analyses of risk and resilience, showing that commonly used formulations address only a small fraction of the possibilities. Means by which a more comprehensive assessment of a system's response to threats can be achieved, are also identified.

This research complements the increasing number of projects and initiatives focused on resilience (including, for example, the '100 Resilient Cities' initiative (Rockefeller Foundation, 2018), the EU-funded IMPROVER (IMPROVER, 2018) and RESILENS (RESILENS, 2018) projects, the EPSRC-funded BRIM network (BRIM, 2018), and the 'Resilience Shift' project funded by Lloyd's Register Foundation (Resilience Shift, 2018)) and contributes to the rapidly growing body of research in this field. The proposed methodology could also be applied to other types of integrated systems analysis (e.g. water, energy, food, waste, climate etc.) and contribute to future developments in these areas.

2. Materials and methods

2.1. Formulating reliability, risk and resilience in the Safe & SuRe framework

For reliability, risk and resilience to be fully defined, it is necessary to specify 'reliability *of what*', 'risk *to what from what*' and 'resilience *of what*' (or 'resilience *of what to what*'), i.e. where the failure and causal event characteristics are measured. This study builds upon the Safe & SuRe framework, as illustrated in Fig. 1, to show the potential failures and their causal events. There are many options and combinations that can be chosen, and all are identified before selection of a set that enables comparable reliability, risk and

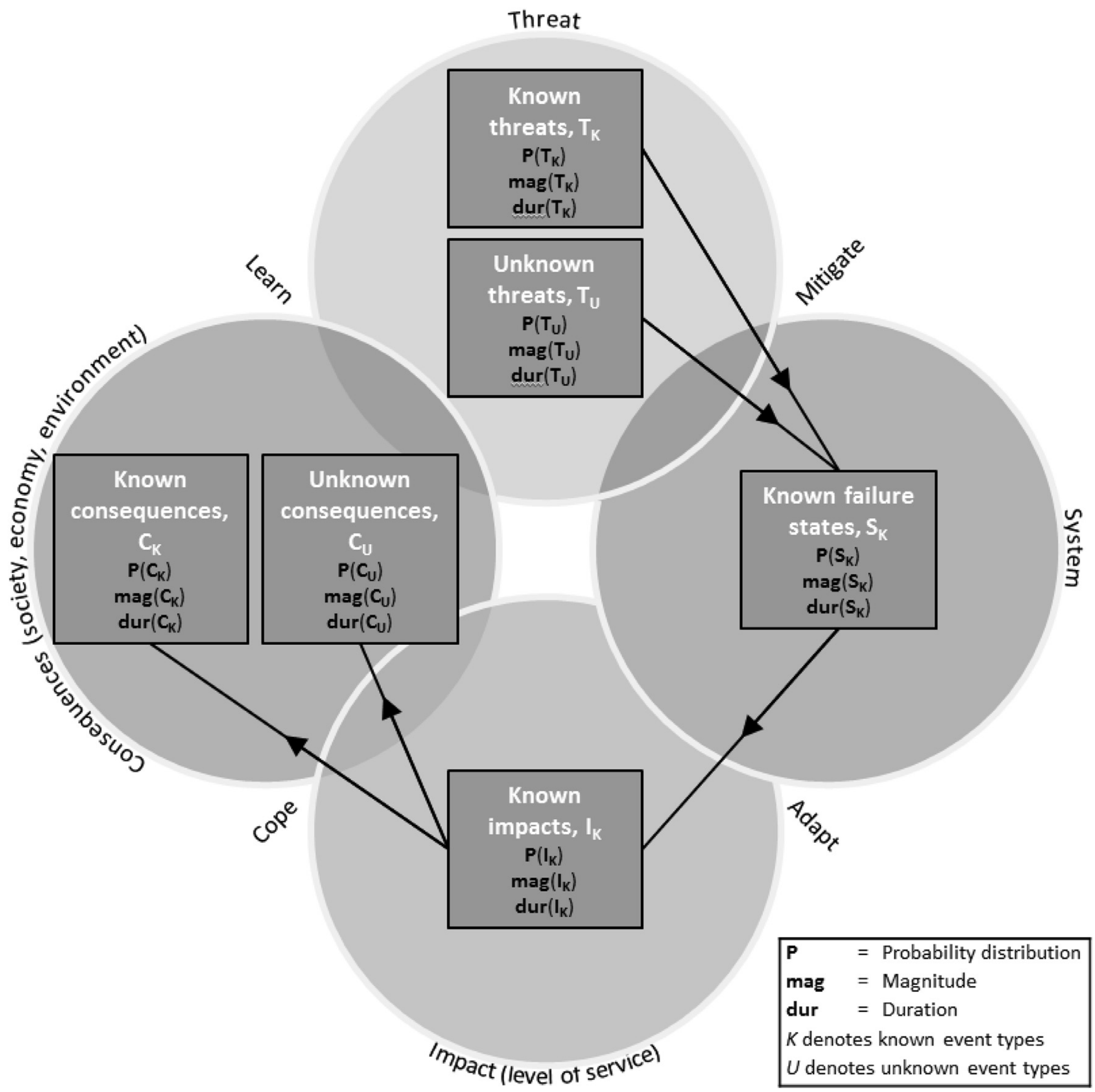

Fig. 1. Potential components of reliability, risk and resilience mapped onto the Safe & SuRe framework.

resilience values to be calculated for the case study IUWS.

In the Safe & SuRe framework, 'threats' are stresses or shocks which may affect the system infrastructure (e.g. a storm event) and can be reduced by mitigation measures; 'impacts' are the effects on level of service resulting from system failures (e.g. pump failure) and may be reduced with adaptation measures; and 'consequences' are the effects on society, the economy and the environment resulting from the impacts (e.g. eutrophication) and may be reduced with coping strategies. An 'event' which may result in a failure could be a threat, a system failure or a change in level of service provision (an impact). 'Failure' could refer to the adverse effects of an event on the system (e.g. physical failure of system components), level of service (i.e. failure to provide the required level of service) or on the society, economy and environment (i.e. adverse consequences).

In the Safe & SuRe framework, threats, system failure states, impacts and consequences are each presented as a single component; however, these can all be further categorised as 'known' or 'unknown', depending on whether or not there is knowledge of their potential existence prior to their occurrence. Known event types include both 'known knowns' and 'known unknowns', where known knowns are well understood and their characteristics identified, and known unknowns poorly understood but known to exist (illustrated in Fig. 2). Attempts to quantify known unknowns may be based on past experience but are subject to uncertainty. Unknowns cannot be characterised since their existence is not recognised. Whilst their existence has been acknowledged, unknown threats and unknown consequences have not previously been considered explicitly or in detail in the Safe & SuRe framework (Butler et al., 2016). Including these two elements in following formulation of reliability, risk and resilience is an important step forward as it facilitates a detailed understanding of all the elements that contribute to of reliability, risk and resilience, and shows the interdependencies between known and unknown threats, (known) system failure modes, (known) impacts and known and unknown consequences. It also clearly illustrates the challenges in providing a comprehensive assessment.

Both known and unknown threats ($\boldsymbol{T_K}$ and $\boldsymbol{T_U}$) and consequences ($\boldsymbol{C_K}$ and $\boldsymbol{C_U}$) exist. However, it is (reasonably) assumed that, for a well-characterised IUWS, all potential system failure states ($\boldsymbol{S_K}$) can be identified (i.e. there are no unknowns and the number of knowns is finite). All types of potential impact ($\boldsymbol{I_K}$) are also

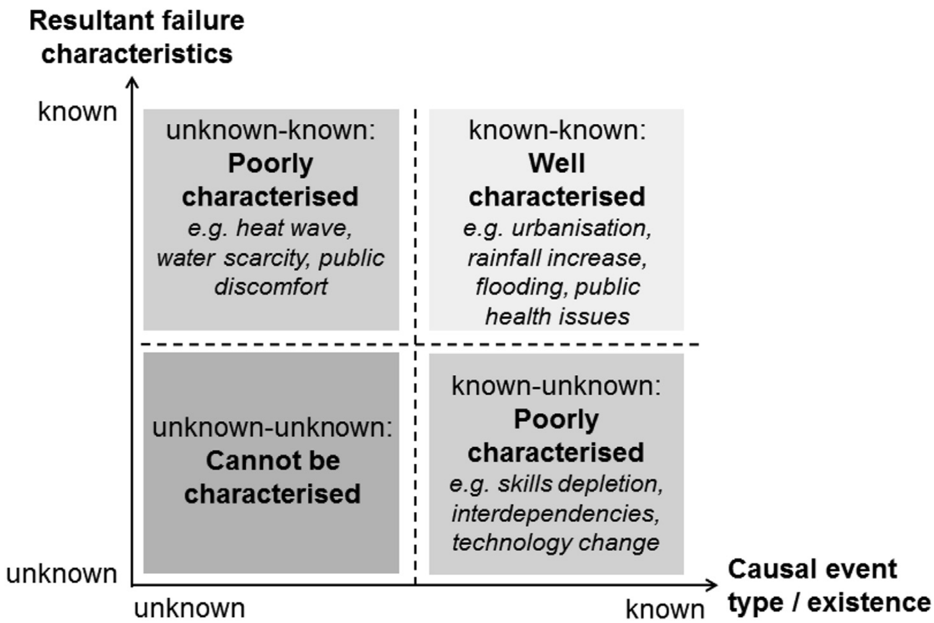

Fig. 2. Known/unknown causal event and failure characteristic matrix; degree of characterisation indicated refer to the causal event(s), examples relate to the 'known' elements (causal events and/or resultant failures).

known since these are based on pre-defined level of service requirements. The interdependencies of these components are shown in Fig. 1: Known system failure states result from both known and unknown threats, known impacts results from known system failure states only, and known impacts can result in both known and unknown consequences.

Note that 'threat', 'system failure state', 'impact' and 'consequence' refer only to the type of event, each of which can encompass a range of different magnitude and duration events of that type. For example, population growth is one potential threat, but this might be 10% or 100%. Although all potential *types* of system failure and impact are known, their characteristics are unknown if the cause is not specified: Due to the chain of events (shown in Fig. 1), all consequences, impacts and system failure states are ultimately affected by both known and unknown threats and hence their characteristics cannot be fully defined. While the types of impact, for example, are all known, the probability, magnitude and duration of these in a general sense cannot be determined since they are partly dependent on unknown threats; it is only possible to determine the probability, magnitude and duration of impacts under specified system failures and/or specified known threats.

A summary of potential events and failures and their characteristics, as may be considered components of reliability, risk and resilience, is given in Table 1. Note that knowledge of the probability distribution function, magnitudes and durations may be incomplete even for known threats, due to the existence of unknown unknowns. Also, known probabilities cannot reasonably cover the complete range of event scales that are theoretically possible since there is likely to be very little data from which a frequency distribution can be derived for particularly rare events (Wang and Blackmore, 2009). Calculation of joint probabilities of two or more major events occurring simultaneously poses an even greater challenge (Park et al., 2013).

Although many possible formulations of reliability, risk and resilience exist, performance metrics can only be calculated for those which do not require knowledge of unknown failure or causal event types or unknown characteristics (probability, magnitude and duration). The following sections, therefore, investigate the components and pre-requisite knowledge required for all formulations possible within the Safe & SuRe framework, to enable identification of those that can and cannot be calculated (theoretically) and facilitate investigation into the relationships between reliability, risk and resilience.

2.1.1. Reliability

Reliability (*Rel*) is defined here as "*the degree to which the system minimises level of service failure frequency over its design life when subject to standard loading*" (Butler et al., 2017). It is typically represented by the probability of success, or probability of a system being in a non-failure state (Hashimoto et al., 1982; Kjeldsen and Rosbjerg, 2004), as in Eq. (1).

$$Rel = 1 - P(failure) \tag{1}$$

In order to calculate reliability, it is necessary to specify where the failure state is measured (i.e. reliability *of what*). Based on the definition given, this should be the level of service (impact). However, there are further options (such as reliability of a specific system component) and, given their common usage, it is useful to identify these too.

Using the Safe & SuRe framework and components identified in Fig. 1, reliability can be formulated in six ways, as detailed in Table 2. Not all reliability measures detailed are useful: it is unclear what would represent a failure with respect to the society/economy/environment, and formulations R5 and R6 are unlikely to be used in practice. However, provided failure limits can be defined, reliability is theoretically calculable using any of the formulations listed since it addresses only performance under standard loading (i.e. known knowns – any event which is rare enough to be a known unknown or completely unknown is not considered standard).

2.1.2. Resilience

The Safe & SuRe definition of resilience, "*the degree to which the system minimises level of service failure magnitude and duration over its design life when subject to exceptional conditions*" (Butler et al., 2017), is used in this study. This contains two components:

Table 1
Potential reliability, risk and resilience components and their characteristics in a Safe & SuRe context. Grey shading represents unknown or incalculable failure or causal event types and characteristics. **P** denotes probability distribution, **mag** denotes set of event/failure magnitudes and **dur** denotes set of failure or causal event durations.

	Failure or causal event type	Failure or causal event characteristics
Failures or causal events occurring under any circumstances	Known threats, $\mathbf{T_K}$	$\mathbf{P}(\mathbf{T_K})$, $\mathbf{mag}(\mathbf{T_K})$, $\mathbf{dur}(\mathbf{T_K})$
	Unknown threats, $\mathbf{T_U}$	$\mathbf{P}(\mathbf{T_U})$, $\mathbf{mag}(\mathbf{T_U})$, $\mathbf{dur}(\mathbf{T_U})$
	Known system failures, $\mathbf{S_K}$	$\mathbf{P}(\mathbf{S_K})$, $\mathbf{mag}(\mathbf{S_K})$, $\mathbf{dur}(\mathbf{S_K})$
	Known impacts, $\mathbf{I_K}$	$\mathbf{P}(\mathbf{I_K})$, $\mathbf{mag}(\mathbf{I_K})$, $\mathbf{dur}(\mathbf{I_K})$
	Known consequences, $\mathbf{C_K}$	$\mathbf{P}(\mathbf{C_K})$, $\mathbf{mag}(\mathbf{C_K})$, $\mathbf{dur}(\mathbf{C_K})$
	Unknown consequences, $\mathbf{C_U}$	$\mathbf{P}(\mathbf{C_U})$, $\mathbf{mag}(\mathbf{C_U})$, $\mathbf{dur}(\mathbf{C_U})$
Failures or causal events occurring under specified circumstances	Known system failures under specified threat, $\mathbf{S_K}\|T_{K,w}$	$\mathbf{P}(\mathbf{S_K}\|T_{K,w})$, $\mathbf{mag}(\mathbf{S_K}\|T_{K,w})$, $\mathbf{dur}(\mathbf{S_K}\|T_{K,w})$
	Known impacts under specified threat, $\mathbf{I_K}\|T_{K,w}$	$\mathbf{P}(\mathbf{I_K}\|T_{K,w})$, $\mathbf{mag}(\mathbf{I_K}\|T_{K,w})$, $\mathbf{dur}(\mathbf{I_K}\|T_{K,w})$
	Known impacts under specified system failure, $\mathbf{I_K}\|S_{K,x}$	$\mathbf{P}(\mathbf{I_K}\|S_{K,x})$, $\mathbf{mag}(\mathbf{I_K}\|S_{K,x})$, $\mathbf{dur}(\mathbf{I_K}\|S_{K,x})$
	Known consequences under specified threat, $\mathbf{C_K}\|T_{K,w}$	$\mathbf{P}(\mathbf{C_K}\|T_{K,w})$, $\mathbf{mag}(\mathbf{C_K}\|T_{K,w})$, $\mathbf{dur}(\mathbf{C_K}\|T_{K,w})$
	Known consequences under specified system failure, $\mathbf{C_K}\|S_{K,x}$	$\mathbf{P}(\mathbf{C_K}\|S_{K,x})$, $\mathbf{mag}(\mathbf{C_K}\|S_{K,x})$, $\mathbf{dur}(\mathbf{C_K}\|S_{K,x})$
	Known consequences under specified impact, $\mathbf{C_K}\|I_{K,y}$	$\mathbf{P}(\mathbf{C_K}\|I_{K,y})$, $\mathbf{mag}(\mathbf{C_K}\|I_{K,y})$, $\mathbf{dur}(\mathbf{C_K}\|I_{K,y})$
	Unknown consequences under specified threat, $\mathbf{C_U}\|T_{K,w}$	$\mathbf{P}(\mathbf{C_U}\|T_{K,w})$, $\mathbf{mag}(\mathbf{C_U}\|T_{K,w})$, $\mathbf{dur}(\mathbf{C_U}\|T_{K,w})$
	Unknown consequences under specified system failure, $\mathbf{C_U}\|S_{K,x}$	$\mathbf{P}(\mathbf{C_U}\|S_{K,x})$, $\mathbf{mag}(\mathbf{C_U}\|S_{K,x})$, $\mathbf{dur}(\mathbf{C_U}\|S_{K,x})$
	Unknown consequences under specified impact, $\mathbf{C_U}\|I_{K,y}$	$\mathbf{P}(\mathbf{C_U}\|I_{K,y})$, $\mathbf{mag}(\mathbf{C_U}\|I_{K,y})$, $\mathbf{dur}(\mathbf{C_U}\|I_{K,y})$

Table 2
Reliability formulations.

Formulation	Failure/non-failure state assessment	Description
R1	Specified system component	Reliability of specified system component
R2	All system components	Reliability of system
R3	Specified impacts	Reliability of specified level of service provision
R4	All impacts	Reliability of level of service provision
R5	Specified (known) consequences	Reliability of specified society/economy/environment component
R6	All known consequences	Reliability of society/economy/environment

failure magnitude and failure duration. It is not necessary to know what causes the failure (although it may be specified) since the probability dimension, as used in risk assessment, is not conventionally included in resilience (Aven, 2011).

Resilience can be specified or general. For general resilience – "*The resilience of any and all parts of a system to all kinds of shocks, including novel ones*" (Folke et al., 2010) – it is necessary to specify resilience *of what* (i.e. where the failure is measured). This encompasses the response to all future threats, including those which are unknown and unforeseeable. 'Resilience of an IUWS', for example, is a measure of the magnitude and duration of effects on the IUWS resulting from *any* threat, including those that cannot be foreseen. For specified resilience – "*resilience of some particular part of a system … to one or more identified kinds of shocks*" (Folke et al., 2010) – resilience *of what to what* (i.e. where the failure state is measured and what the causal event considered is) must be specified. An example would be 'resilience of an IUWS to storm events', in which the magnitude and duration of the effects of the storm events on the IUWS determine the resilience value.

Possible points in the Safe & SuRe framework which the failure magnitude and duration may relate to are shown in Fig. 3. In Fig. 3a, the cause of the failure (causal event) is specified: these formulations, therefore, relate to specified resilience. General resilience uses the formulations in Fig. 3b, since the failures here can result from anything.

Resilience cannot be calculated in formulations in which the magnitude and duration of the failure are unknown; however, knowledge of the probability of the causal event is not required. Therefore, resilience can (theoretically) be calculated under twelve different formulations (S1-S2, S4 and S7-S12 in Fig. 3a and G2 and G5-G6 in Fig. 3b).

Haimes (2009) argues that general resilience cannot be calculated, since it requires knowledge of the response to any threat, but this is not always the case. Resilience cannot be calculated under formulation G3 (resilience of society, economy and the environment), as this requires knowledge of unknown consequences, and G1 and G4 (resilience of system and resilience of specified system component) are also incalculable since not all threats which may cause system failures are known. However, the framework presented illustrates that general resilience can be calculated through a middle state based analysis, as in G2 and G5, as both known and unknown threats result in the same known, finite set of system failure modes. Take, for example, formulation G2, resilience of level of service. This may be modelled as 'resilience of level of service to any threat', which cannot be calculated since not all threats are known, but also as 'resilience of level of service to any system failure', which can be calculated as all the modes by which the system may fail are identifiable; what threat (known or unknown) causes them is irrelevant since, by evaluating all system failure modes, the potential effects of all threats are captured. Multiple threats can thus be addressed with analysis of a smaller number of system failure modes.

Traditionally, resilience has focussed on the failure of assets; however, asset failure may not necessarily affect level of service provision and may be irrelevant from a consumer perspective (Ofwat, 2010). This suggests that, although formulation S1 may be of interest to the asset owners, an impact or consequence based approach (such as G5 or G6) is of greater benefit. Similar applies to reliability and risk.

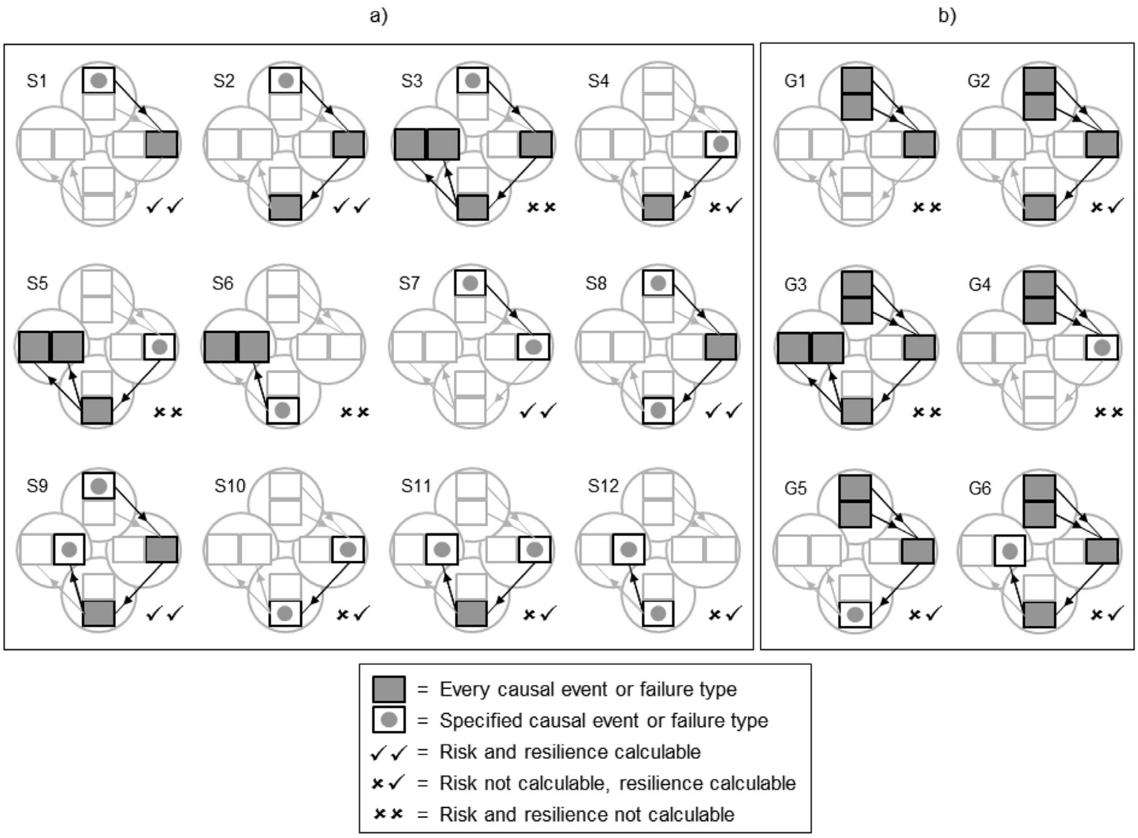

Fig. 3. Possible combinations of failure location and causal event in the Safe & SuRe framework: a) with specified (known) cause of failure, as required for specified risk or specified resilience; b) with any cause of failure, as required for general risk or general resilience. Refer to Fig. 1 for interpretation of circular framework diagrams. Detailed descriptions are provided in the Supplementary Information.

2.1.3. Risk

Definitions and use of the term 'risk' are inconsistent. Whilst risk is conventionally calculated as a function of probability and consequence of a given scenario (Kaplan and Garrick, 1981), often in practice the severity of the resultant adverse effects are not accounted for. Konstantinou et al. (2011), for example, defined risk as the conditional probability of incurring loss or damage under certain unfavourable circumstances, and in terms of practical application, the Environment Agency's flood risk maps (Environment Agency, 2018) show only the probability of flooding (with no indication of severity). Such an approach may be acceptable when knowledge of the degree of the damage is not required (e.g. if knowing simply whether or not flooding occurs, irrespective of depth, is sufficient). However, it is also argued that risk should provide a measure of the potential losses or adverse effects (Scholz et al., 2011) and it is generally quantified using a function of event frequency and effect magnitude (Blackmore and Plant, 2008); this is the interpretation used in this work.

The following equation, adapted from the typical 'probability x consequence' to fit the terminology of this study, is used here to represent risk.

$$Risk = P(casual\ event) \times magnitude(failure) \quad (2)$$

In calculation of risk, the casual event probability and failure magnitude could be measured at different locations: for example, when calculating the risk of a combined sewer overflow (CSO) resulting from a storm event, 'failure' could refer to either the occurrence of a CSO or the occurrence of deterioration in the receiving water body quality; in the case of the former, the causal event could be considered the storm event, whereas for the latter either the storm event or the CSO could be considered as the causal event. Hence, for absolute clarity, it is necessary to specify risk *to what from what* (i.e. where the effect is measured and the potential cause of that considered).

For conventional risk calculation, both the probability of the causal event and the magnitude of its effects (the failure) need to be known and measurable. Accordingly, Fig. 3 illustrates all potential combinations of 'failure' and 'causal event' within the Safe & SuRe framework and identifies those which result in a calculable risk formulation. Similarly to resilience, risk formulations in which a specific causal event is identified may be classified as 'specified risk', and those which address risk from *any* (known or unknown) event can be classified as general risk. Risk cannot be calculated in formulations which include unknown threats in the causal events (i.e. the 'general' formulations, G1-G6 in Fig. 3b) since, by definition, these cannot be characterised; this is in contrast to resilience, where it is not necessary to know, for example, the probability of the events that may result in failures. Similarly, risk cannot be calculated in formulations that include unknown consequences in the measured failures (i.e. formulations S3-S6, S9 and S11 in Fig. 3a, and G3 in Fig. 3b). Furthermore, risk cannot be calculated if the required causal event probability or failure magnitude is unknown despite the existence of the causal event or failure type being known (formulations S10 and S12 in Fig. 3a). This leaves five formulations (S1, S2 and S7–S9 in Fig. 3a) under which risk may be calculated in the Safe & SuRe framework. Further details, including equations for each formulation, are provided in the Supplementary Information.

2.2. Conceptual relationships

2.2.1. Reliability and risk

There is widely assumed to be a connection between reliability and risk. However, the nature of this relationship is less clear. Some consider increasing reliability to be analogous to decreasing risk, for example, with high risk equating to low reliability (Konstantinou et al., 2011). However, others consider reliability a contributor to risk, as it contributes to the probability of failure, but is not the only component (Zio, 2013). This corresponds with the risk assessment approach of Kjeldsen and Rosbjerg (2004), and suggests that, although increasing reliability may contribute to a reduction in risk, other factors must also be considered.

2.2.2. Reliability and resilience

Reliability may be considered a prerequisite and/or a component of resilience (Butler et al., 2017; Francis and Bekera, 2014), or alternatively a complementary performance indicator (e.g. Kjeldsen and Rosbjerg, 2004). As for risk, this suggests that increasing reliability may contribute to efforts to increase resilience but additional measures are also required.

2.2.3. Risk and resilience

Resilience is differentiable from but complementary to risk analysis (Park et al., 2013); however, there is often overlap and confusion in use of the two terms, and resilience analysis in practice is commonly based on the concept of risk. The Overseas Development Institute (Mitchell and Harris, 2012), for example, have published a 'risk management approach' to resilience, and Halcrow, (2008) have produced a 'Service Risk Framework' for assessment of resilience.

Fig. 3 highlights the broader scope of resilience assessment: risk can only be calculated under five of the eighteen possible formulations and cannot account for unknown threats, whereas resilience can be calculated under nine (including all for which risk can be calculated). Risk cannot be calculated under formulations S4 and S10-12 (amongst others) since these require knowledge of probabilities that cannot be determined ($\mathbf{P}(S_{K,x})$ and $\mathbf{P}(I_{K,y})$); despite the event type being specified and known in these cases, its probability is not known as it may occur as a result of unknown threats (the probabilities of which are not known). Resilience *can* be calculated under formulations S4 and S10-12, however, since this does not require knowledge of the probability of the event(s) resulting in failure.

Risk cannot be calculated under the formulations used for general resilience (G2, G5 or G6) since knowledge of the probability of unknown threats is required in every case. Even if the probability can be expressed as the probability of infrastructure failure or probability of level of service failure (as in G6, for example), it is still affected by unknown threats and cannot be calculated. To be calculable, risk must be specified. General resilience formulations could be considered more useful for detailed system analysis, since they include a measure of the response to *any* threat, including unknowns, but they are also more challenging to calculate for this very reason.

2.2.4. Reliability, risk and resilience

Based on the definitions and discussion in Section 2.1, the conceptual relationships between reliability, risk and resilience with respect to the probability and magnitude of events addressed are presented graphically in Fig. 4. Reliability concerns performance under 'standard loading', which will typically cover the relatively low magnitude, high probability events which are expected to occur within the system's design life. Risk can address more extreme events with a lower probability and higher magnitude, but still cannot deal with events that are considered too unlikely to be assigned a probability with any degree of certainty or events that cannot be foreseen. Resilience can address the same events as risk assessment but, as it is not necessary to know the probability, can also consider the system response to and recovery from much more extreme events (including so called 'black swans') which, although highly unlikely, *may* occur.

2.3. Integrated urban wastewater system case study

2.3.1. Case study

The case study IUWS used (shown diagrammatically in Fig. 5) is a semi-hypothetical system that was originally presented by Schütze et al. (2002) and has since been the subject of many studies (e.g. Butler and Schütze, 2005; Fu et al., 2008; Zacharof et al., 2004). It comprises a sewer system, a wastewater treatment plant with an off-line pass through storage tank at the inlet, and a river (of which 45 km is modelled). It was simulated using SIMBA6 (IFAK, 2009). It should be noted that, as the model is of a semi-hypothetical system and risk and resilience assessments are based on the modelling of extreme events, including those that have not previously happened, the complete integrated model cannot be calibrated and the results cannot be validated using data from real events.

Performance evaluation is based on simulation of a seven day rainfall event with a total depth of 27 mm. Dynamic outputs used are the dissolved oxygen (DO) and ammonium concentrations in the river. Un-ionised ammonium concentration is estimated from the total ammonium using a conversion factor of 0.0195 (based on a pH of 7.7 and a temperature of 20 °C (Schütze et al., 2002). Further details on the IUWS model simulation are given by Astaraie-Imani et al. (2012).

Ten operational control and design parameters (detailed in Table 3) are used as decision variables and sampled using Latin Hypercube Sampling to produce a set of 400 options for evaluation in this study. These parameters include four sewer storage tank volumes, maximum pumped outflow from each storage tank (above which CSOs occur), maximum flow to the wastewater treatment plant (WWTP) and the WWTP influent threshold triggering emptying of the storm tank. Upper and lower limits for operational decision variables are extended beyond those typically considered so as to provide a greater range of reliability, risk and resilience values. It is recognised that this approach may produce many solutions with poor performance; however, it should also yield options providing a high level of performance and it is important that a wide range is captured so as to gain a more complete picture of the relationships between reliability, risk and resilience.

2.3.2. Reliability, risk and resilience formulation

In order that reliability, risk and resilience can be compared, it is important that compatible formulations are used for each. For risk and resilience, formulation S2 (*risk to level of service from specified threat* and *resilience of level of service to specified threat*) is chosen since this requires no knowledge of unknowns and can be calculated. For reliability, the corresponding formulation is R4 (*reliability of level of service provision*).

All require measures of failure characteristics and must, therefore, consider the same level of service requirements to be comparable. In all formulations, receiving water quality represents the level of service and level of service failure is classified as the occurrence of a DO concentration less than 4 mg/l (Fu et al., 2008) and/or an un-ionised ammonia concentration greater than 0.068 mg/l (Johnson et al., 2007). The specified threat considered for risk and resilience is population increase, which is modelled as an increase in dry weather flow (DWF). The reliability, risk and

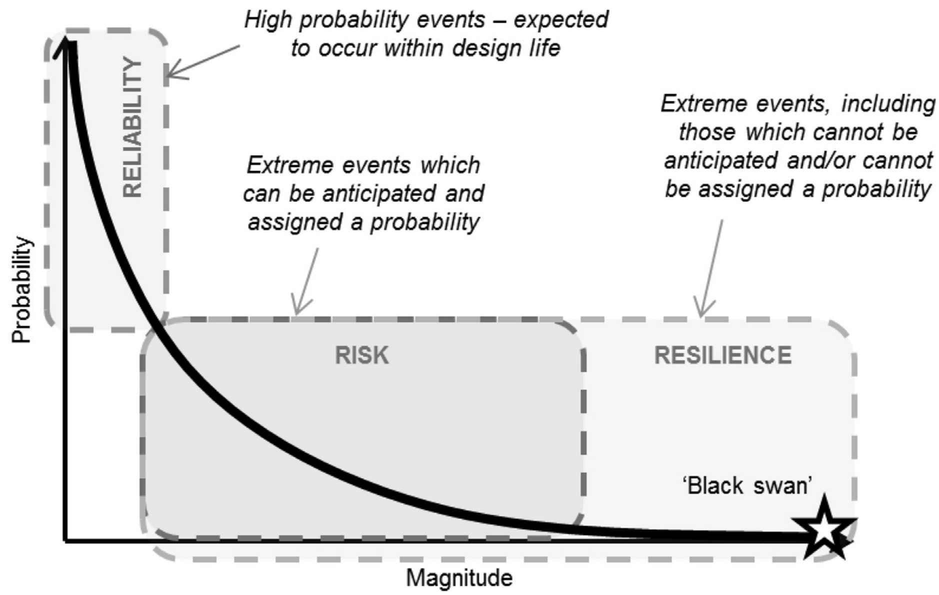

Fig. 4. Conceptual relationships between reliability, risk and resilience with respect to the probability and magnitude of events addressed.

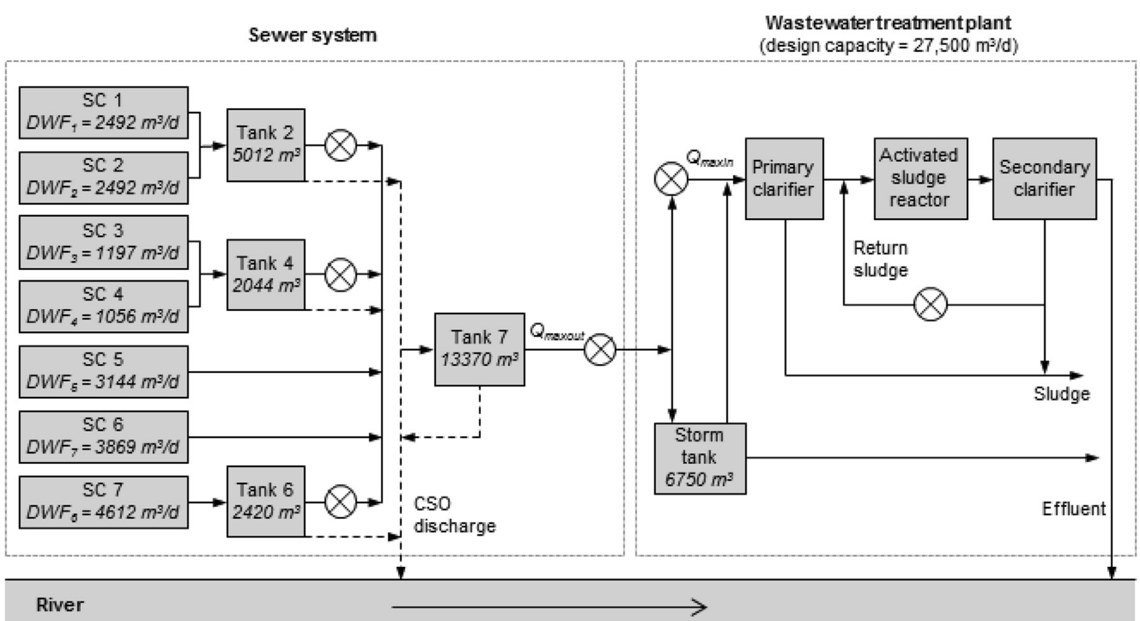

Fig. 5. Schematic diagram of the semi-hypothetical IUWS case study, with base case dry weather flows (units m^3/d) and tank volumes indicated. SC denotes subcatchment.

Table 3
Operational control and design decision variables DWF denotes base case dry weather flow in the corresponding subcatchment(s) and DC the WWTP design capacity, as indicated in Fig. 5.

	Decision variable	Description	Value range
Design	V_{ST2}	Storage tank 2 vol increase (%)	[0, 100]
	V_{ST4}	Storage tank 4 vol increase (%)	[0, 100]
	V_{ST6}	Storage tank 6 vol increase (%)	[0, 100]
	V_{ST7}	Storage tank 7 vol increase (%)	[0, 100]
Operational control	Q_{ST2}	Maximum outflow from tank 2 before CSO (m^3/d)	[3 × $DWF_{1,2}$, 8 × $DWF_{1,2}$]
	Q_{ST4}	Maximum outflow from tank 4 before CSO (m^3/d)	[3 × $DWF_{3,4}$, 8 × $DWF_{3,4}$]
	Q_{ST6}	Maximum outflow from tank 6 before CSO (m^3/d)	[3 × DWF_6, 8 × DWF_6]
	Q_{maxout}	Maximum outflow from tank 7 before CSO (m^3/d)	[3 × DC, 8 × DC]
	Q_{maxin}	Maximum flow to primary clarifier (m^3/d)	[0.5 × DC, 5 × DC]
	Q_{trig}	WWTP influent threshold triggering emptying of the storm tank (m^3/d)	[4800, 40800]

resilience values calculated can, therefore, be explicitly defined as follows:

- Reliability of receiving water quality compliance
- Risk to receiving water quality from population increase by 2035
- Resilience of receiving water quality to population increase

Note that it is necessary to define the time frame for risk assessment since population increase probabilities are time dependent.

The measured failure characteristics will be different in each case as each must consider different causal event scenarios: reliability relates to failures under 'standard' loading whereas risk relates to failures under foreseeable conditions and resilience relates to failures under exceptional conditions.

It is acknowledged that use of a resilience formulation which incorporates response to unknowns (e.g. G2) would be preferable; however, this would not allow risk to be calculated and compared on a like-for-like basis.

2.3.3. Reliability, risk and resilience assessment

A brief description of the assessment methodologies is provided here; further detail is available in the Supporting Information.

2.3.3.1. IUWS reliability assessment. Reliability is assessed under standard conditions (i.e. no population increase) using Eq. (1), where the probability of failure is based on the modelled level of service failure duration.

2.3.3.2. IUWS risk assessment. Risk is evaluated for population increases of 0–15% at 1.5% intervals, using Eq. (2). In each case, the probability of population growth equalling or exceeding the given value is calculated based on 95% prediction intervals reported by the United Nations (Raftery et al., 2012; United Nations, 2012) for the UK population in 2035, assuming a normal distribution. The greater of the normalised DO deficit and normalised un-ionised ammonia exceedance represents the failure magnitude. This yields 16 risk values for each IUWS operational control and design option, the highest of which is used in the following analysis.

2.3.3.3. IUWS resilience assessment. Assessment of resilience is based on the concept of using a response curve (system performance as a function of disturbance magnitude) for comparison of solutions (Diao et al., 2016; Mugume et al., 2015), where the area under the curve provides a measure of resilience. To capture both the magnitude and duration components of resilience, failure characteristics are measured using two metrics, $P_{deficit}$ (based on mean performance deficit) and $P_{duration,mean}$ (based on mean failure duration), each of which are calculated for population changes in the range 0–150%. This yields two resilience indicators for each option, $R_{deficit}$ and $R_{duration,mean}$.

3. Results and discussion

3.1. Reliability, risk and resilience relationships

Fig. 6 shows the relationships between reliability, risk and resilience for the 400 IUWS operational control and design options evaluated: each circle represents a different option, the colour of the circle represents its reliability value, and its x and y coordinates show its risk and resilience values respectively. Fig. 6a utilises the resilience indicator based on mean performance deficit and Fig. 6b the resilience indicator based on mean failure duration.

Fig. 6 shows that an increase in reliability typically corresponds with reduced risk and increased resilience in this system, for the reliability, risk and resilience formulations considered ($r = -0.91$ for reliability and risk, $r = 0.97$ for reliability and $R_{deficit}$, and $r = 0.95$ for reliability and $R_{duration,mean}$). However, most levels of reliability can be achieved with a range of different risk and resilience values, showing the importance of considering performance under extreme conditions as well as standard loading. Additionally, risk and resilience values shown in Fig. 6 reveal a correlation ($r = -0.92$ for risk and $R_{deficit}$, $r = -0.83$ for risk and $R_{duration,mean}$), but they are not directly proportional – hence risk assessment cannot be considered a substitute for resilience assessment. With respect to the system design and operational control, it is desirable that the same option provides the highest reliability, lowest risk and highest resilience: This section explores the feasibility of this goal and the observed relationships between reliability, risk and resilience.

3.1.1. High reliability options

In Fig. 6b, reliability greater than 0.999 can be achieved with 30 operational control and design options, yet the resilience ($R_{duration,mean}$) values of these options range from 0.85 to 0.92. This is attributed to variation in the DO failure characteristics resulting from the different design and operational control options: Whilst the DO failures are observed with a 15% population increase in the lower resilience option, DO failures in the higher resilience option are not recorded until population increase reaches 45%, and are then of significantly shorter magnitude and duration.

3.1.2. High reliability, low risk options

In Fig. 6b, resilience ($R_{duration,mean}$) values range from 0.87 to 0.92 for options with reliability greater than 0.999 and risk below 0.001. This indicates that there is significant variation in the resilience of options providing low risk *and* high reliability (particularly noticeable with the $R_{duration,mean}$ resilience indicator). Therefore, these results demonstrate that, when selecting design and operational control options for an IUWS, high reliability and low risk are necessary criteria but not sufficient for high resilience; resilience must be considered as a third and separate objective.

If, in this case study, no benefit of considering the three performance measures as separate objectives had been found, this would not provide sufficient evidence to conclude that (in the wider sense) reliability, risk and resilience do not all need to be considered in the design and operation of IUWSs. However, the observation here that they cannot be used interchangeably is sufficient to demonstrate that the highest reliability and lowest risk options do not necessarily provide the highest resilience.

3.1.3. High resilience options

Fig. 6a and b also show that there can be significant variation in the risk and reliability values for options providing a given level of resilience. For example, in Fig. 5b, options providing a resilience ($R_{duration,mean}$) value of 0.85 have reliability values in the range 0.910–1.000 and risk values in the range 0.023–0.176. This suggests that consideration of greatest resilience alone is insufficient and reliability and/or risk must also be evaluated to ensure that the chosen option performs well under a wide range of conditions, including standard loading. This observation is particularly important when it is not possible to implement the option providing the greatest resilience (e.g. due to cost restraints), as there is greater range in risk and reliability for lower resilience options.

The different levels of resilience, risk and reliability provided by

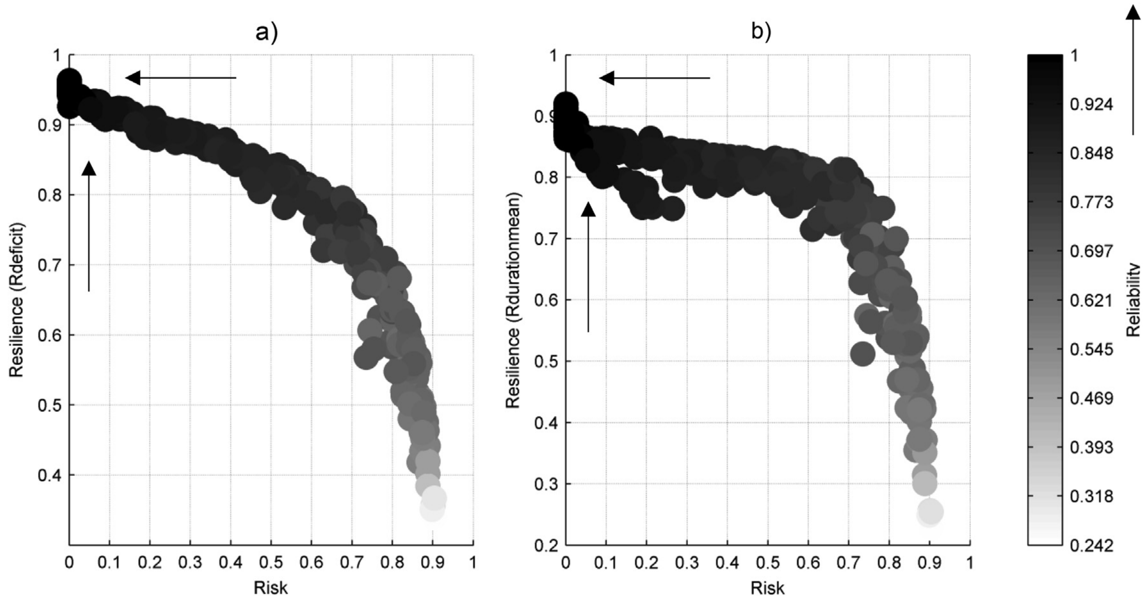

Fig. 6. Relationships between reliability, risk and resilience ($R_{deficit}$ and $R_{duration,mean}$) in the case study IUWS; arrows indicate direction of improved performance.

each option are attributed to adjustment in the decision variables presented in Table 3. When analysing the options providing a resilience ($R_{duration,mean}$) value of 0.85 (as above), the option providing highest reliability and lowest risk has larger values for Q_{maxin}, Q_{ST2}, Q_{ST4} and Q_{ST6}. This will result in a smaller volume of CSOs from subcatchments 1–4 and 7, as well as a greater volume of wastewater being treated, thereby resulting in higher receiving water quality under standard conditions. However, it only provides the same level of resilience as that provided by a less reliable option with greater CSOs and less wastewater treated, whereas it would intuitively be expected to provide higher resilience than a less reliable option. This may be attributed to it resulting in a greater impact on level of service under extreme population increase as the surcharged WWTP performs poorly and low quality discharge is concentrated at the WWTP outlet instead of distributed along the river by CSOs.

3.2. Reliability-, risk- and resilience-based design

Most operational control and design options shown in Fig. 6 do not represent realistic solutions, given their poor performance even under standard loading/design conditions. Further analysis, therefore, focuses on those which provide good performance under the base case population (i.e. have high reliability).

Example response curves for three options which provide a reliability of at least 0.999 are shown in Fig. 7. The first (grey line) provides a high degree of reliability only. The second (black line) is also low risk (risk $\leq$ 0.001), and the third (bold, dashed line) is the option that provides the highest level of resilience whilst also providing high reliability and low risk. These show that a high degree of reliability does not guarantee good performance under disturbances; consideration of risk improves the response but resilience assessment is required to ensure the chosen option

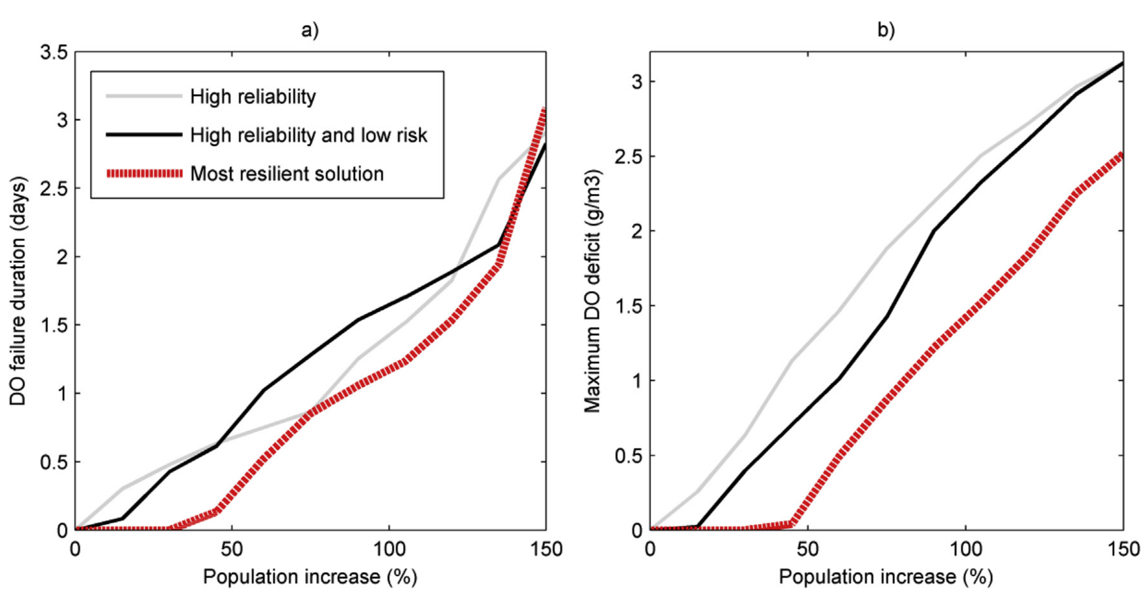

Fig. 7. DO response to population increase for high reliability, low risk and high resilience options.

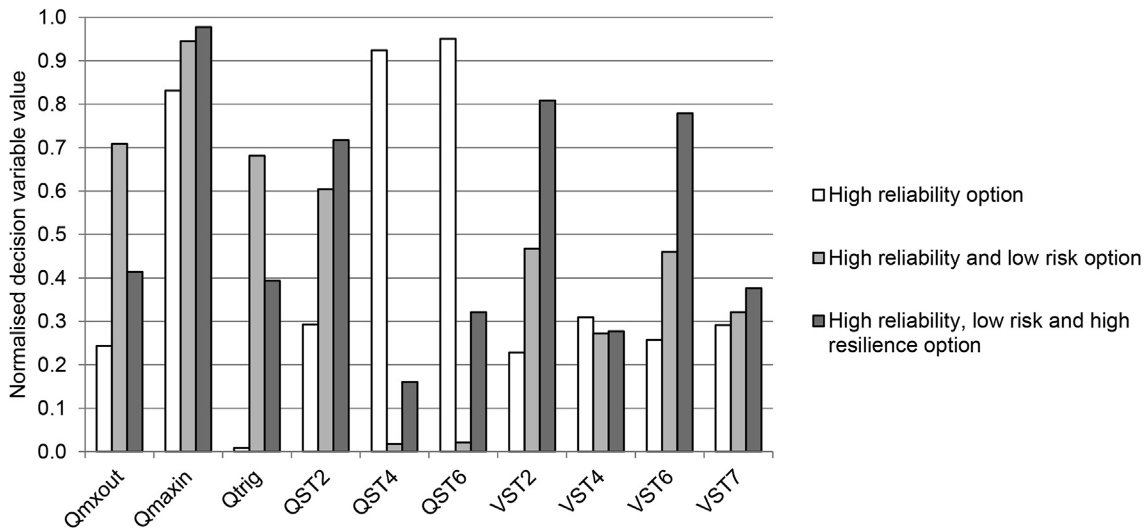

Fig. 8. Decision variable values for options providing: a) high reliability, b) high reliability and low risk, and c) high reliability, low risk and high resilience.

performs well with respect to alternatives when water quality failures do occur. The difference between reliability-, risk- and resilience-based IUWS design is most marked in Fig. 7b, where the control and design option resulting in the greatest DO deficit (minimum DO concentration) under any level of population increase has high reliability but not low risk, and the most resilient solution maintains the highest DO concentration (minimises the failure magnitude) under any population increase.

To illustrate the potential differences between reliability-, risk- and resilience-based design, the decision variable values of the three different options are shown in Fig. 8. The high reliability option provides a receiving water quality compliance reliability of 1.000, risk to receiving water quality from population increase of 0.023 and a receiving water quality resilience to population increase ($R_{duration,mean}$) of 0.853. The high reliability and low risk option has reliability, risk and resilience values of 1.000, 0.000 and 0.868 respectively, and in the high resilience option the resilience ($R_{duration,mean}$) is increased to 0.922. It is shown that, whilst there are similarities between the three options (most notably in Q_{maxin} and V_{ST7}), the characteristics of the operational control and design option providing high resilience differ from those providing just high reliability. For example, high reliability can be achieved with an increase in storage volume of 23–31% (V_{ST2}, V_{ST4}, V_{ST6} and V_{ST7}); however, significantly greater increase in storage volume is required to provide the highest level of resilience.

This suggests that identification of preferable design and operational control options, taking into account reliability, risk and resilience, requires an understanding of the mechanism of failure minimisation (i.e. how the different options reduce the frequency, magnitude and duration of failure), and that there may be cost implications of increasing resilience (e.g. due to extra storage required).

Note that observations on the relationships between reliability, risk and resilience in the IUWS case study are based on a formulation of resilience that addresses only one known threat. The capability of a middle-state based resilience assessment to address multiple threats, including unknowns (as in formulation G2, for example), has not been exploited. The benefits of a 'high resilience' approach over a 'low risk' approach are expected to be greater if resilience is calculated using a formulation under which risk is incalculable (e.g. S4, S10 or G2), but demonstrating the benefits is challenging if they are not observable until the occurrence of a previously unknown threat. Even under risk and resilience formulation S2, however, it is shown that failure magnitude and duration under a specified threat can be significantly reduced by considering resilience in addition to risk.

4. Conclusions

This research has explored the ways in which reliability, risk and resilience may be formulated, identifying possible components and knowledge required for calculation of each and formalising the conceptual relationships between specified and general resilience. A set of corresponding formulations has also been implemented in a case study IUWS to enable investigation into the relationships between reliability, risk and resilience for this system. The following conclusions are drawn:

- Many formulations of both general and specified risk and resilience exist, but not all can be calculated due to the existence of unknown threats and unknown consequences.
- General resilience can theoretically be calculated (under some formulations) whereas general risk cannot. Resilience can, therefore, address responses to a wider range of threats.
- All threats, including both known and unknown, can be addressed with a middle-state based resilience analysis which focusses on the level of service response to system failures. Risk cannot be calculated on the same basis since the probability of system failure is affected by the probability of unknown threats.
- Consideration of resilience in addition to risk can be beneficial even when only considering specified threats, as demonstrated in the case study. Lowest risk solutions do not necessarily provide the highest specified resilience.
- Although reliability, risk and resilience values may exhibit correlations, designing for just one is insufficient: reliability, risk and resilience are complementary measures.

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Appendix A. Supplementary data

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